Preface

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Abstract.

The Photochemistry of Ozone Loss in the Arctic Region In Summer (POLARIS) mission was designed to investigate the natural summer decrease of stratospheric ozone levels. Both polar regions have large and distinct annual cycles of ozone column amounts. In northern spring, the average level is over 450 Dobson units (DU), decreasing to less than 275 DU by September. In order to cover this period of ozone decrease, POLARIS was conducted in three deployment phases from Fairbanks, Alaska, (65°N) during the summer of 1997. The principal measurement platforms were the NASA ER-2 high-altitude aircraft and stratospheric balloons. Additional measurements were provided by ground-based instruments, sondes, and satellites. POLARIS observations included ozone, meteorological variables, particles, long-lived chemicals, and short-lived radicals. During the field deployments, several modeling and theoretical groups participated in flight planning and data evaluation activities. The interpretive studies in this Special Section of the Journal of Geophysical Research are a first comprehensive examination of the POLARIS data set, addressing stratospheric ozone abundances and its changes; the role of aerosols; details of the photochemistry of reactive species; transport of stratospheric air and the correlations of long-lived species; and measurement intercomparisons.

Introduction

Ozone both screens the Earth from the biologically harmful effects of solar ultraviolet radiation and is a radiatively active gas in both the UV and the IR portions of the solar spectrum. Changes in global ozone amounts will impact both greenhouse warming severity and the Earth's biota [*WMO,* 1999]. Hence, a precise understanding is needed of how changes in atmospheric composition (e.g., aircraft emissions or anthropogenic trace gas releases) might cause ozone changes. This requires a thorough understanding the chemistry and transport processes that control ozone in the stratosphere.

The polar stratospheres are unique regions for ozone because of the cold continuous darkness in winter and the warm continuous daylight in summer. In winter, stratospheric temperatures are quite low (see e.g., *Coy et al.* [1997a]), enabling a variety of chemical reactions to occur on polar stratospheric cloud particles [*Peter,* 1997; *Poole and Pitts,* 1994]. The continuous daylight in polar summer enables a much different chemical environment than is observed at similar times in mid-latitudes or the tropics [*Farman et al.,* 1985; *Johnston,* 1975; *Fahey and Ravishankara,* 1999]. The summer polar temperatures in the lower stratosphere are quite warm and the mean circulation is in an easterly flow (e.g., see *Wu et al.,* [1984]). In addition, eddy flux quantities (such as the heat flux) show that the transport is considerably weakened (again, see *Wu et al.,* [1984]). Weakened dynamics results in a much reduced transport of ozone from the tropical photochemical production region into the Arctic lower stratosphere [*Wu et al.,*

1987; *Gettelman et al.,* 1997]. However, significant wave effects have been observed in ozone and other trace gases, where low ozone was correlated with high NO [*Park and Russell,* 1994], implying important roles for both photochemical and transport effects.

Ozone abundances show a distinct seasonal cycle in areas away from the tropical ozone production region. At northern high latitudes, ozone column amounts peak in spring and reach minimum values in late summer/early fall [*Dobson et al.,* 1929; *London et al.,* 1976; *Krueger,* 1989; *Bojkov,* 1988] (see Figure 1). This spring-to-fall Arctic decrease was first recognized following the pioneering spectrophotometer measurements of Dobson and his colleagues [*Dobson et al.,* 1929]. The decrease is attributed to an increased role of NO_x catalytic cycles in ozone destruction during periods of prolonged solar illumination at summer polar latitudes [*Johnston,* 1975] and reduced poleward transport of ozone. Increased NO_x also moderates the effectiveness of the Cl_x (= Cl + ClO) and HO_x (= OH + HO_2) ozone loss cycles [*Brühl et al.,* 1998]. However, model simulations of this decrease have generally overestimated ozone in the polar region [*Chipperfield,* 1999]. The winter-to-spring build-up of ozone was originally ascribed to a mean poleward and downward transport effect by *Brewer* [1949] and *Dobson* [1956], and later refined with the development of the "transformed Eulerian mean" circulation [*Edmon et al.,* 1980; *Dunkerton et al.,* 1981]. While conventional meteorological data have been used to validate the winter build-up of ozone at high latitudes, less progress has been made in validating the photochemical loss of ozone over the course of the summer.

Figure 1

The POLARIS mission was designed to understand the photochemical and

transport processes that cause the summer polar decreases in stratospheric ozone. The mission primarily utilized the NASA ER-2 high-altitude aircraft and balloon platforms while based in Fairbanks, Alaska. Additional data were obtained with ground-based instruments, satellites, and sondes. Measurements included meteorological variables; long-lived tracers for assessing summertime transport questions; reactive species within the reactive nitrogen (NO_y), halogen (Cl_y), and hydrogen (HO_x) reservoirs; and aerosols. These stratospheric measurements were made at mid- to high latitudes in spring and summer. These observations have been combined with various computer models of the atmosphere to evaluate summer ozone changes due to chemistry and transport.

Following this introduction to the POLARIS mission are sections that acknowledge the programmatic background of the mission, describe the mission logistics, provide highlights of the separate deployment phases, describe the science topics included in the papers accompanying this Special Section, and summarize the overall mission .

Program background

POLARIS was sponsored by the National Aeronautics and Space Administration through its Upper Atmosphere Research Program (UARP), Atmospheric Effects of Aviation Project (AEAP), and Atmospheric Chemistry Modeling and Analysis Program (ACMAP) in cooperation with the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF).

NASA's support follows from its Congressional mandate "to provide for an understanding of and to maintain the chemical and physical integrity of the Earth's

upper atmosphere." NASA has developed and continues to implement a long-range scientific research program aimed at providing a comprehensive understanding of atmospheric processes occurring throughout the upper troposphere and stratosphere. As the experimental component of this NASA program, UARP focuses on process-study investigations with the specific objective of understanding the chemical, physical, and transport processes within these regions and their control on the distribution of atmospheric species such as ozone. Such understanding enables the prediction of possible perturbations to atmospheric composition caused by human activities and natural phenomena. AEAP is further mandated to develop a scientific basis for the assessment of the effects of aviation on ozone and climate.

UARP-sponsored research falls into three categories: field measurements, laboratory studies, and process study modeling and data analysis. Campaigns such as POLARIS constitute a major component of UARP field measurements. In the past two decades, significant measurement results have been derived from campaigns such as the Stratosphere Troposphere Exchange Project (STEP); the Airborne Antarctic Ozone Experiment (AAOE); the first and second Airborne Arctic Stratospheric Expeditions (AASE I and II); the Stratospheric Photochemistry, Aerosols, and Dynamics Expedition (SPADE); the Airborne Southern Hemisphere Ozone Experiment / Measurements for Assessing the Effects of Stratospheric Aircraft (ASHOE-MAESA); the Stratospheric Tracers of Atmospheric Transport airborne experiment (STRAT) and concurrent balloon campaigns such as the Observations from the Middle Stratosphere (OMS) campaigns. Since many of the AEAP scientific objectives are encompassed by the broader goals

of UARP, a strong UARP/AEAP field measurement partnership was fostered for ASHOE-MAESA, STRAT, and OMS and continued for POLARIS.

NASA's UARP, NASA'S AEAP, and Japan's NASDA provided support for two balloon flights from Fairbanks carrying a variety of instruments during the April-May POLARIS phase. The flights, which were designed to provide correlative observations for the Japanese Advanced Earth Observing Satellite (ADEOS), also provided data of value for POLARIS.

Mission description

The principal measurement platforms for POLARIS were the NASA ER-2 aircraft and balloons. The four balloon flights included the two supporting the ADEOS satellite correlative measurements, one of the NASA OMS in-situ payload, and one flight of the OMS remote payload. Small balloons also were used for ozone sondes throughout the mission.

Spatial and temporal coverage

The 35 ER-2 and 4 balloon flights during the POLARIS campaign covered the entire summer period and latitudes from the equator to the pole (see Table 1). Table 1

Figure 1 displays the flight tracks of the NASA ER-2 (black lines) superimposed on an image of the total ozone concentrations from the Earth Probe Total Ozone Mapping Spectrometer (TOMS) instrument. The three deployment phases of POLARIS are seen as the groupings of the black lines in Figure 1 and are also noted in Table 1. The phases

occurred in April-May (Phase I), June-July (Phase II), and September (Phase III). Most of the flights were flown from Fairbanks, Alaska (65°N), with a few flown from the NASA Ames Research Center (ARC) (37°N), and one flight flown to 3°S from Barbers Point, HI (21°N). The region of continuous (24-hour per day) sunlight is indicated by the white line in Figure 1. Deployment Phase I occurred after continuous daylight began at the north pole, Phase II was timed to the summer solstice when continuous daylight was covering the maximal amount of the polar area, and Phase III was timed to cover the disappearance of continuous polar daylight at summer equinox.

The altitudes sampled during POLARIS extended from the surface to approximately 20 km for the ER-2, and up to 30 km for the ADEOS and OMS balloon flights. Figure 2 displays the altitude profiles of the ER-2 and balloon flights (white thin lines). These altitude profiles are superimposed on ozone partial pressure contours as derived from the separate ozone sonde launched from Fairbanks. The three phases of POLARIS are seen again in the groupings of the lines over the course of the summer period. The ADEOS and OMS balloon flights are labeled on the figure, and are also differentiated from the ER-2 flights by the greater maximum altitudes.

The POLARIS flights covered latitudes from 3°S to 90°N (see Table 1). Figure 3 shows the three POLARIS deployment sites, the latitude/longitude extent of all mission flights, and the May-September 1997 average of TOMS total ozone. ADEOS and OMS balloon flights were all launched from Fairbanks and generally landed near to Fairbanks depending on wind speeds. The ozone sondes were launched at the University of Alaska in Fairbanks throughout the April to September period and with higher frequency during

the deployment phases [*Lloyd et al.,* 1999]. The launch dates are indicated by the dark triangles at the bottom of Figure 2. These sondes provided near-continuous monitoring of overhead ozone amounts over the course of the three POLARIS deployments.

During the mid-summer period, the polar region is surrounded by a maximum of ozone near 60°N as is apparent in Figure 3 (see e.g., *Godson,* [1960]). Fairbanks is located poleward of this maximum in the region where ozone decreases by a large amount between spring and fall. Hence, POLARIS was staged from Fairbanks because of the proximity to the region of continuous sunlight and the region of large spring to fall ozone change.

The evolving meteorological fields influenced the planning of ER-2 flight paths and launch opportunities for the balloons. Because clearance into Russian controlled airspace was difficult to obtain, flights were also restricted to the western hemisphere. An important parameter choosing air masses to be sampled on ER-2 flights was the extent of solar exposure received by an air mass in the preceding five to ten days. This and other flight planning tools were utilized to sample a gradient in solar exposure and reach maximum possible values.

Airborne payloads

The list of POLARIS ER-2 Principal Investigators, the measured parameters, and the measurement technique are listed in Table 2. This payload provides measurements of radical, reservoir, and source gases in all of the major stratospheric families (chlorine, bromine, nitrogen, oxygen, and hydrogen). In addition, measurements of the UV

Table 2

and visible solar spectrum, particle number and size, and meteorological variables provided necessary data for fully detailing the dynamics and chemistry of the lower stratosphere. The POLARIS ER-2 payload was expanded over that of previous missions with the addition of both in situ and remote measurements. New in situ measurements included $ClONO_2$ and an additional measurement of NO_2 (Harvard Univ.) The $ClONO_2$ measurements are the first to be made in situ in the stratosphere [*Stimpfle et al.*, 1999]. New remote measurements include those of the submillimeter limb sounder (SLS). With the exception of the SLS instrument, the payload in Table 2 was flown on all POLARIS flights. SLS and a small subset of the full payload were flown on the ER-2 transit flights between Moffett Field, CA, and Fairbanks between the Phase I and II, and Phase II and III deployments.

The POLARIS OMS activities made use of a remote sensing payload and an in-situ measurements payload (see Table 3). The in-situ payload focused on measurements of long-lived trace gases for investigating stratospheric transport issues. The remote payload combined an in situ ozone measurement with the long-path absorption measurements of the MkIV Fourier transform interferometer (FTIR) (see Table 3). The MkIV FTIR measured a wide range of radicals, reservoir species, and long-lived trace gases.

Table 3

The ADEOS correlative balloon flights included two payload configurations, both including remote and in situ instruments (see Table 4). The payloads were flown on 30 April 1997 and 8 May 1997.

Table 4

Ground-based observations

Ground-based instruments of ozone column amounts were provided by two spectrophotometers at Fairbanks (Table 4) during and between the deployment phases in conjunction with the UV and visible radiation measurements made on the ER-2 *Lloyd et al.* [1999]. Between deployment phases, the MkIV FTIR instrument was also used on the ground at Fairbanks to measure many of the molecules listed in Table 4.

Satellite investigations

Satellite and ground station measurements of ozone form the backbone of the global ozone monitoring system. These ozone data are essential information for global monitoring of stratospheric ozone change [*WMO,* 1999]. Linking the POLARIS observations to satellite and ground-based measurements was important ito establishing an overall understanding of the evolution of polar ozone from spring to fall. The Earth Probe TOMS, ADEOS TOMS, the Upper Atmosphere Research Satellite (UARS) Halogen Occultation Experiment (HALOE), the UARS Microwave Limb Sounder (MLS), and Stratospheric Aerosol and Gas Experiment (SAGE II) instruments all provided ozone measurements that contributed to POLARIS field and analysis activities (see Table 4). In addition, HALOE and SAGE II measured other species that were also measured by the ER-2 and balloon instrument payloads. For example, NO_2 was measured by SAGE II, HALOE, the MkIV FTIR, and two instruments aboard the ER-2 (see Tables 2, 3, and 4).

Theoretical investigations

Accurate meteorological forecasts and theoretical modeling of the stratosphere were important aspects of the POLARIS mission. Meteorological forecasts by the GEOS-1 model of the NASA/GSFC Data Assimilation Office were used in the detailed flight planning of the ER-2 [*Coy et al.,* 1997a; *Coy et al.,* 1997b]. Analyses derived from this same assimilation system were used to compute air mass trajectories [*Schoeberl et al.,* 1993], and to detail the evolution of the stratospheric meteorological conditions over the course of the summer. In addition, satellite cloud images and forecast data were used to forecast the movement of cirrus cloud systems. All of this information was transferred, exchanged , and integrated on field workstation computers used for flight planning.

Models of the chemical and photolysis fields provided a basis for comparison to observations. These model predictions and post-flight comparisons to data revealed key agreements and discrepancies that have been subsequently utilized to confirm and refine our understanding of the stratosphere. The Principal Investigators for modeling and forecasting activities are detailed in Table 5.

Forecasting air motions in the winter stratosphere is principally done using potential vorticity and temperatures [*Tuck et al.,* 1989]. During summer, the weak easterly circulation, lack of a well defined vortex, and lack of a distinctive cold air region makes accurate forecasting quite difficult. Because the chemistry is dependent on the continuous sunlight, new forecast products were developed to find air masses that had undergone continuous sunlight for extended periods. These "solar exposure fields"

utilized GEOS-1 model forecast information to calculate the time that air parcels had been exposed to sunlight with solar zenith angles less than 92°. The fields are calculated using a 1°latitude by 1°longitude grid of points with an isentropic trajectory model [*Newman and Schoeberl*, 1995; *Schoeberl and Newman*, 1995] that integrates the amount of sunlight encountered by an air mass over a 10 day period. As an example, the flight of 13 May is superimposed on the solar exposure field in Figure 4. The flight was planned to cross an air mass which was moving southward from the pole to North America. This air had received nearly continuous exposure for 10 days. The flight track bearing was slightly east of north to further encounter an air mass that recently come northward from the eastern hemisphere. All of the POLARIS "photolysis" flights (see Table 1) were planned using these solar exposure fields. Such products and the conventional meteorological products were the tools used for planning the POLARIS flights.

Figure 4

Deployment Descriptions

Phase I: April-May. This ER-2 flight series covered a latitude range from 13°N to 90°N at cruise altitudes near 20 km in the lower stratosphere. On most flights, vertical coverage extended from approximately 15 to 21 km at selected latitudes. Several full vertical profiles were obtained between cruise altitude and the surface at the two deployment sites, ARC (37°N) and Fairbanks (65°N).

A number of POLARIS objectives were achieved in this phase. First, the ER-2 penetrated the northern polar vortex on 26 April 1997 during a flight that reached the north pole. In the spring of 1997, the polar vortex had unusually low ozone and

persisted for an exceptionally long period (see *Geophysical Research Letters, 24* [1997] for a series of articles describing these low ozone values). Second, the ER-2 completed flights that separately included a sunrise (30 April 1997) and sunset (9 May 1997) at high latitudes in the stratosphere. The data indicated unusual asymmetries in the behavior of hydrogen radicals at low-angle solar illumination. Third, the ER-2 sampled stratospheric air masses that had experienced continuous sunlight for periods ranging from 1 to 12 days (2, 6, and 13 May 1997). These flights revealed important observational-model (photochemical steady-state and trajectory) discrepancies with respect to NO_x concentrations. Fourth, there were two successful launches of the ADEOS balloon payloads.

Phase II: June-July. With the ER-2 based solely in Fairbanks during Phase II, the latitude survey range extended from 47.7°N to 90°N in the lower stratosphere. Vertical coverage to 21 km in the Fairbanks region was quite good because of dedicated flights on 30 June 1997 and 10 July 1997 that included a number of flight legs at specific altitudes in the upper troposphere and lower stratosphere. In addition, vertical profiles were obtained over the 15- to 20-km altitude range near 47.7°N and 90°N.

POLARIS objectives were achieved in this phase included sampling of mid-summer polar air that had undergone continuous solar exposure for an extended period; OMS balloon flights using the in situ and MkIV FTIR payloads to altitudes in excess of 30 km (performed coincidentally with ER-2 flights); and sampling of winter polar vortex fragments in mid-summer.

Phase III: September. Phase III ER-2 flights included latitudes extending from 90°N to 3°S in the lower stratosphere. Both sunrise and sunset flights in late summer were conducted over the Fairbanks region, similar to those flown in Phase I. In addition, a midday solar zenith angle flight was flown, providing a nearly full scan of solar zenith angles from sunrise to sunset in similar air masses.

As the final component of this phase, the ER-2 transited to Barbers Point, Hawaii, performed a flight to slightly south of the equator, and returned to ARC. Vertical profiles from the ground to 21 km occurred at Fairbanks, Hawaii, and ARC, with profiles over the 15- to 20-km altitude range near 3°S and 90°N.

POLARIS Science topics

This collection Journal of Geophysical Research papers is the first to interpret the POLARIS data set in a comprehensive manner. These papers address stratospheric ozone abundances and its changes; the photochemical role of aerosols; details of the photochemistry of reactive species; transport of stratospheric air and the correlations of long-lived species; and measurement intercomparisons. Data from ground-based instruments and those on the ER-2 aircraft, balloons, satellites, and sondes are included, thereby representing the full range of available observational data. In addition, many papers rely directly or indirectly on meteorological analyses. Box models, trajectory models, and 2-D and 3-D photochemical transport models are widely used to add value to the observations. Finally, these papers are augmented by several that have or will be published separately since the end of the POLARIS field campaign [*Gao et al.*,

1999; *Osterman et al.*, 1999; *Wennberg et al.*, 1999; *Hurst et al.*, 1999; *Hintsa et al.*, 1999; *Nevison et al.*, 1999].

The most extensive observations available for POLARIS are those of ozone in column and profile abundances. Each data set clearly marks the late spring-to-summer decline in ozone amounts. Intercomparisons show good systematic agreement among the various data sets [*Lloyd et al.*, 1999; *Toon et al.*, 1999a; *Toon et al.*, 1999b].

The ozone observations form the basis for addressing an important objective of POLARIS: Are the observed summer ozone decreases consistent with our understanding of transport and chemical processes? With the papers included here, a fully consistent picture has yet to emerge [*Pierce et al.*, 1999; *Rosenlof*, 1999; *Toon et al.*, 1999a; *Hitchman et al.*, 1999]. However, the combination of models and observations confirm the role of photochemistry in summer ozone decreases at high latitudes. In general, ozone amounts throughout the stratosphere represent a balance of transport and photochemical production and destruction processes. The photochemical contribution was calculated directly or deduced as a difference between net ozone changes and the transport contribution. Similarly, transport contributions can be calculated directly from the residual circulation which usually brings air to high latitudes from lower latitudes or deduced as a difference using calculated photochemical changes. In addition, column ozone amounts change as a result of synoptic waves disturbing the tropopause region [*Hitchman et al.*, 1999].

The large number of long-lived and radical species measured during POLARIS provide an unprecedented opportunity to diagnose photochemical processes and measure

trace species abundances in the summer high latitude stratosphere [*Del Negro et al.*, 1999; *Jucks et al.*, 1999; *Randeniya et al.*, 1999; *Sen et al.*, 1999; *Stimpfle et al.*, 1999; *Swartz et al.*, 1999; *Gao et al.*, 1999; *Osterman et al.*, 1999; *Wennberg et al.*, 1999; *Hurst et al.*, 1999; *Hintsa et al.*, 1999; *Drdla et al.*, 1999]. A highlight of the results are the analyses of the partitioning of the NO_y and Cl_y reservoirs. The enhanced and uninterrupted solar illumination at summer high latitudes increases the abundance of NO_x within the NO_y reservoir and the associated catalytic ozone loss. Comparisons using box models constrained by observations and other models showed unsatisfactory agreement when using currently recommended kinetic rate coefficients. More recent measurements of the rates of the gas-phase reactions of OH with NO_2 and HNO_3 by *Brown et al.*, [1999] and *Dransfield et al.*, [1999] have substantially improved the agreement in most comparisons. The sunrise and sunset flights revealed the need for an additional HOx source in current models. The source could be the long-wavelength (¿650 nm) photolysis of HNO4. The NO_y analyses benefited from two in situ measurements of NO_2 on board the ER-2 aircraft which showed good agreement throughout the mission and were consistent with the NO observations. The evaluations of the partitioning within the Cl_y reservoir demonstrate a good understanding throughout the lower stratosphere. New in situ measurements of $ClONO_2$ on the ER-2 aircraft were an important addition to these analyses. An analysis of the hydrogen budget also shows good agreement in the lower stratosphere.

Aerosols play a lesser role in the chemistry of the summer stratosphere because N_2O_5 formation becomes negligible in regions of continuous solar illumination [*Farman*

et al., 1985; *Gao et al.*, 1999; *Osterman et al.*, 1999]. However, the summer stratosphere provides a unique opportunity to evaluate aerosol processes at warm temperatures (> 210K). The results suggest no new significant role of aerosol processes in the summer but highlight the need for more further study of several potentially important reactions [*Drdla et al.*, 1999]. Measurements of soot particles on the ER-2 aircraft significantly enhanced available observations in the lower stratosphere [*Strawa et al.*, 1999]. The results suggest that reactions on soot particles likely do not have a significant role in controlling the partitioning with the NO_y reservoir in agreement with previous studies.

Special features of the POLARIS mission are the sampling of air from tropical latitudes in late spring and late summer and from the Arctic vortex in late April. These new data from aircraft and balloons extend data sets acquired in previous missions and with other platforms. The papers here use these new data sets in part to address transport of air into the tropics and within high latitudes [*Andrews et al.*, 1999; *Flocke et al.*, 1999; *Ray et al.*, 1999; *Rex et al.*, 1999; *Romashkin et al.*, 1999]. Tropical and mid-latitude measurements of species with a wide range of lifetimes were used to quantify the rate of transport of air from mid latitudes to the inner tropics. The results indicated more rapid transport into the tropics than found in earlier studies. Measurements of CO_2 were used to evaluate the vertical age distribution in the tropical lower stratosphere. SF_6 and CFC observations were used in a unique analysis to estimate the fraction of air in the lowermost stratosphere at midlatitudes which is from the tropical troposphere and from the stratospheric overworld. With long-lived tracer correlations of CH_4, NO_y, and N_2O, mixing processes associated with the Arctic

polar vortex were clarified with a specific emphasis on validating the occurrences of denitrification. Correlations and age-of-air information were also used to clarify how stratospheric abundances of methyl chloroform are changing in response to changes in tropospheric emission rates.

Summary

The POLARIS mission was conducted over the course of the 1997 summer. The POLARIS ER-2 aircraft and OMS balloon flights provide an unprecedented glimpse of polar summer chemistry, dynamics, and radiation. The logistic success of POLARIS is demonstrated by the 35 ER-2 and 4 balloon flights completed over the late spring and summer period and by the large body of data that has been archived from the wide variety of airborne, satellite, and balloon data and model results.

The natural decrease of ozone over the course of the summer has been well documented by decades of ground and satellite observations. The chemistry and dynamics of the summer period have only been partially understood from a theoretical basis, and limited satellite observations. The new POLARIS observations have firmly grounded our theoretical expectations with a large body of new observational evidence.

The papers included in this Special Section attest to the scientific success of POLARIS. The papers address key issues concerning the photochemistry and transport in the stratosphere and provide important new detail of the causes underlying changes in summer ozone amounts.

A highlight of the photochemical investigations is the detailed comparison of radical

and reservoir measurements with models. These results initially revealed important discrepancies and agreements in our understanding of stratospheric chemistry. These observations encouraged new laboratory measurements, which have led to revised reaction rate recommendations that significantly improve model performance. These model improvements provide greater confidence in our predictions of future stratospheric change.

POLARIS and other NASA sponsored missions are described at the NASA Ames Earth Science Division Project Office web site (http://cloud1.arc.nasa.gov/). The POLARIS data set and data sets from all the mission prior to POLARIS are available on CD-ROM by request from the NASA Ames Earth Science Division Project Office.

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duty toward making POLARIS a success. Finally, we recognize Kathy Wolfe's tireless effort in negotiating hotel accommodations for over 100 persons, coordinating important mission activities in preparation for POLARIS and in the field deployments, and in organizing the POLARIS Science Team meeting in Snowmass, Colorado, in June 1998.

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Figure 1. Values of total column ozone from the Total Ozone Mapping Spectrometer (TOMS) instrument on the Earth Probe satellite shown as a function of time and latitude during 1997. Contour lines are labeled in Dobson Units (DU, m-atm cm) and separated by 15 DU. No observations are available for the white open areas at high latitudes. The dark vertical lines represent ER-2 flight tracks during POLARIS. The thick white line denotes the boundary of continuous daylight.

Figure 2. Values of ozone in milli-Pascal (mPa) as a function of time and pressure altitude (pressure) during the April to September period of 1997. Contours are separated by 2 mPa. Observations are from ozone sondes launched from Fairbanks, Alaska, (65°N) on dates marked by yellow triangles at the bottom of the figure. The thin white vertical lines represent the altitude range of ER-2 flights during POLARIS. The thin white lines extending to the top of the image represent the ADEOS and OMS balloon flights. The thick white horizontal line represents the tropopause.

Figure 3. TOMS total ozone averaged from May 1997 through September 1997. Fairbanks, AK, was the principal POLARIS basing site, with a series of test flights from NASA/Ames, and a single flight to the equator flown from Barber's Point, HI. All of the POLARIS ER-2 flights are shown in black.

Figure 4. Solar exposure field for 13 May 1997. The colors represent the fraction of time spent by an air parcel in sunlight over the period 03-13 May (see scale on left). The ER-2 flight of 13 May is superimposed on this field as the thick black line.

Table 1. POLARIS Flight Log

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
			Phase I		
970416	ER-2	2.00	97-01	35°- 38°N	check flight
970418	ER-2	5.00	97-02	36°- 38°N	check flight
970422	ER-2	7.75	97-03	14°- 38°N	south survey from ARC
970424	ER-2	6.00	97-04	37°- 66°N	Transit ARC to FAI
970426	ER-2	8.00	97-05	65°- 90°N	N. Pole—Into vortex
970430	ER-2	6.50	97-06	64°- 65°N	Sunrise
970430	ADEOS	8.77	429N	65°N	Correlative balloon
970502	ER-2	7.58	97-07	65°- 71°N	Photolysis—Canada
970506	ER-2	6.83	97-08	65°- 79°N	Photolysis—Canada
970508	ADEOS	8.55	431N	65°N	Correlative balloon
970509	ER-2	6.17	97-09	64°- 65°N	Sunset
970511	ER-2	4.92	97-10	62°- 65°N	Stack
970513	ER-2	6.67	97-11	65°- 85°N	Photolysis—North
970515	ER-2	5.33	97-12	65°- 37°N	Transit FAI to ARC

Table 1. (continued)

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
			Phase II		
970623	ER-2	5.25	97-13	37°- 65°N	Transit ARC to FAI
970626	ER-2	7.75	97-14	55°- 77°N	Photolysis—North
970629	ER-2	6.75	97-15	48°- 65°N	Photolysis—South
970630	OMS	5.78	435N	65°N	In situ balloon
970630	ER-2	4.58	97-16	63°- 67°N	OMS comparison
970704	ER-2	8.25	97-17	48°- 71°N	Photolysis—North/South
970707	ER-2	8.00	97-18	65°- 90°N	Photolysis—North
970708	OMS	6.93	436N	65°N	MkIV balloon
970710	ER-2	5.50	97-19	64°- 65°N	Stack
970712	ER-2	5.50	97-20	65°- 37°N	Transit FAI to ARC
			Phase III		

Table 1. (continued)

Date	Type	Flight Hours	POLARIS Flight	Lat.	Comments
970902	ER-2	5.50	97-21	37°- 65°N	Transit ARC to FAI
970908	ER-2	7.75	97-22	65°- 86°N	Photolysis
970910	ER-2	0.50	97-23	64°- 65°N	Abort after takeoff
970911	ER-2	4.25	97-24	64°- 65°N	Sunset flight
970914	ER-2	6.40	97-25	64°- 65°N	Sunrise
970918	ER-2	8.00	97-27	65°- 90°N	Photolysis—North Pole
970919	ER-2	7.30	97-28	64°- 65°N	East/West
970921	ER-2	7.33	97-29	65°- 21°N	Transit FAI to BP
970923	ER-2	8.00	97-30	21°N - 3°S	South survey
970925	ER-2	6.00	97-31	21°- 37°N	Transit BP to ARC

Table 2. POLARIS ER-2 Instrument Payload

PI	Institution	Instrument	Measurements	Technique
J. Anderson E. Hintsa	Harvard	H_2O	H_2O	Lyman-α hygrometer
J. Anderson P. Wennberg	Harvard	HO_x	OH, HO_2	Chemical titration and laser-induced fluorescence
J. Anderson, R. Stimpfle, R. Cohen	Harvard and UC-Berkeley	$ClONO_2$	$ClONO_2$, ClO , NO_2	Resonance fluorescence, chemical titra and thermal dissociation Laser-induced fluorescence
E. Atlas	NCAR	WAS	hydrocarbons, halocarbons, organic nitrates	Whole air canister sample with labora analysis by gas chromatography and m spectrometry
K. Boering, S. Wofsy	Harvard	CO_2	CO_2	Non-dispersive infrared absorption

Table 2. (continued)

PI	Institution	Instrument	Measurements	Technique
P. Bui	NASA ARC	MMS	pressure, winds, temperature	External aircraft probes ports
J. Elkins	NOAA CMDL	ACATS	CFC-11, CFC-12, CFC-13, CH_3CCl_3, CCl_4, Halon 1211, SF_6, H_2, N_2O, CH_4	Gas chromatography, ele detection
B. Gandrud	NCAR	MASP	particle number and size (0.4–10 μm diameter)	Light scattering by indiv
R.-S. Gao	NOAA AL	NO_y	NO, NO_2, NO_y	NO-O_3 chemiluminescen photolysis for NO_2, catal
B. Gary	NASA JPL	MTP	temperature profiler	Microwave radiometer
M. Loewenstein	NASA ARC	ATLAS	N_2O	Tunable diode laser abso
R. May	NASA JPL	H_2O	H_2O	Open path, far-infrared a

Table 2. (continued)

PI	Institution	Instrument	Measurements	Technique
C. T. McElroy	AES, Canada	CPFM	solar radiation	UV and visible spectroradi
M. Proffitt	NOAA AL	O_3	O_3	Ultraviolet light absorptior
R. Stachnik	NASA JPL	SLS	O_3, H_2O, HNO_3, ClO	Submillimeter-wave emissi
A. Strawa	NASA ARC	APS	particle number and size (>0.1 μm diameter)	Wire impaction and electr analysis
C. Webster	NASA JPL	ALIAS	HCl, N_2O, CH_4, CO	Tunable diode laser absorp
J. Wilson	Denver	CNC	condensation nuclei particles	Particle growth followed by scattering
J. Wilson	Denver	FCAS	particle number and size (0.08–2 μm diameter)	Light scattering by individ

Table 2. (continued)

PI	Institution	Instrument	Measurements	Technique

Table 3. POLARIS OMS Balloon Observations

PI	Institution	Instrument	Measurements	Technique
		in-situ		
K. Boering, S. Wofsy	Harvard	CO_2	CO_2	Non-dispersive infrared absorpt
J. Elkins	NOAA CMDL	LACE	CFC-11, CFC-12, CFC-13, SF_6	Gas chromatography with elect capture detection
M. Loewenstein	NASA ARC	ARGUS	N_2O, CH_4	Tunable diode laser absorption
J. Margitan	NASA JPL	O_3	O_3	Ultraviolet absorption
S. Oltmans	NOAA CMDL	H_2O	H_2O	Frost-point hygrometer
C. Webster	NASA JPL	ALIAS II	N_2O, CH_4	Tunable diode laser absorption
		remote		

Table 3. (continued)

PI	Institution	Instrument	Measurements	Technique
G. Toon	NASA JPL	MkIV	O_3, N_2O, HNO_3, NO_2, CH_4, H_2O, CO, CFC-11, N_2O_5, H_2O_2, HOCl, $ClONO_2$, HCl, HF, CFC-12, NO, HNO_4, OCS, HCN, CCl_4, CF_4, COF_2, $CHFCl_2$, CH_3Cl, C_2H_2, C_2H_6, O_2, N_2, H_2CO, HCOOH, HDO, SF_6, CFC-113, CH_3Cl	Solar infrared absorption
J. Margitan	NASA JPL	O_3	O_3	Ultraviolet absorption

Table 4. POLARIS Collaborative Measurement Programs and Platforms

PI	Institution	Instrument	Measurements	Technique/ Satellite
			ADEOS Correlative Balloon Measurement - 30 April 1997	
M. Hayashi	Nagoya	Aerosol	particle size and number	Filter/impactor measuremer
J. Margitan	NASA JPL	O_3	O_3	Ultraviolet absorption
R. Stachnik	NASA JPL	SLS	O_3, N_2O, HNO_3, HO_2, ClO, HCl	Submillimeter limb sounder
W. Traub	SAO	FIRS-2	O_3, N_2O, HNO_3, NO_2, H_2O, N_2O_5, OH, HO_2, H_2O_2, HOCl, $ClONO_2$, HCl, HF	Far-infrared spectrometer
			ADEOS Correlative Balloon Measurement - 8 May 1997	
F. Murcray	Denver	CAESR	O_3, HNO_3, CH_4, CFC-11,	Mid-infrared remote therma

Table 4. (continued)

PI	Institution	Instrument	Measurements	Technique/ Satellite
			CFC-12, N_2O_5, aerosol	grating spectrometer
G. Toon	NASA JPL	MkIV	CO_2 and 22 of the 33 species listed in table 3	Solar infrared absorption
M. Hayashi	Nagoya	Aerosol	particle size and number	Filter/impactor measure:
		POLARIS correlative ground and ozonesonde measurements		
D. Jaffe S. Oltmans	U. Alaska NOAA CMDL	ozonesondes	P, T, O_3	Electrochemical cell
C. T. McElroy	AES, Canada	Brewer	O_3	UV spectra
R. Benner	U. Alaska	Dobson	O_3	Differential UV

Table 4. (continued)

PI	Institution	Instrument	Measurements	Technique/ Satellite
G. Toon	NASA JPL	MkIV	See table 3	Solar infrared absorptio
		POLARIS Satellite Measurement Investigators		
P. McCormick	Hampton	SAGE II	NO_2, aerosols	ERBS
R. McPeters	NASA GSFC	TOMS	column O_3	Earth Probe
R. Pierce	NASA LaRC	HALOE	O_3, NO, NO_2, H_2O, CH_4, HCl, HF	UARS
R. Pierce	NASA LaRC	MLS	O_3, HNO_3, ClO	UARS
Y. Sasano	JAE/NIES	ILAS	O_3, HNO_3, NO_2, N_2O, H_2O, CFC-11, CH_4, aerosols	ADEOS

Table 4. (continued)

PI	Institution	Instrument	Measurements	Technique/ Satellite

Table 5. POLARIS Modeling and Forecast Projects

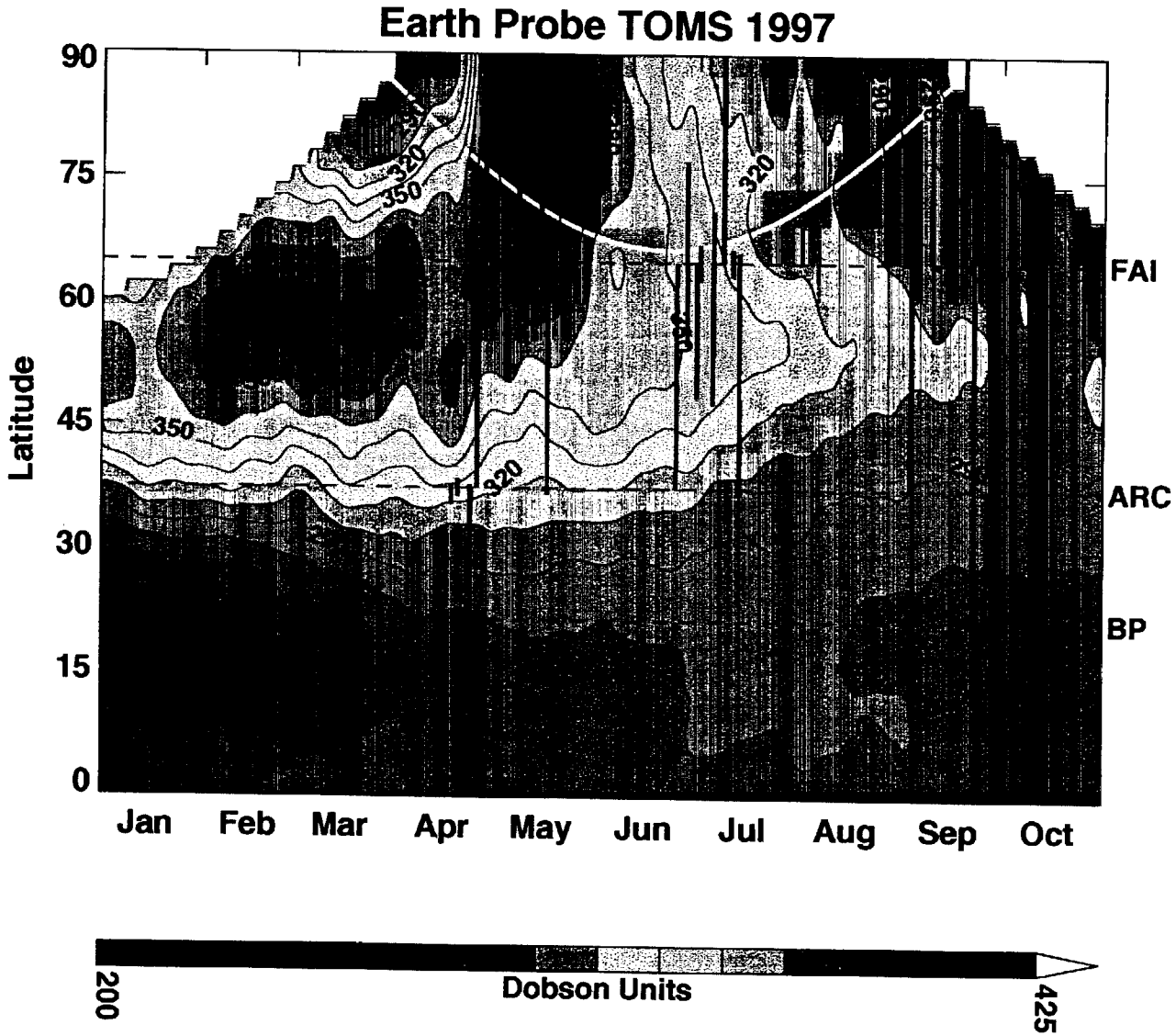
PI	Institution	Project Description
B. Brune	Penn State	OMS project scientist
D. Fahey	NOAA AL	POLARIS co-project scientist
M. Hitchman	Wisconsin	Non-Hydrostatic modeling of summer stratospheric mixing processe
R. Kawa	NASA GSFC	3-D chemical transport and chemistry on trajectory modeling
		AEAP Program scientist
M. Ko	AER, Inc.	Contribution to data analysis using AER 2-D assessment model
M. Kurylo	NASA HQ	UARP manager and POLARIS program scientist
	NIST	
S. Lloyd	Johns Hopkins	Radiative and photochemical modeling

Table 5. (continued)

PI	Institution	Project Description
P. Newman	NASA GSFC	POLARIS co-project scientist Meteorological forecasting, flight planning, and data analysis
L. Pfister	NASA ARC	Meteorological satellite data support
R. Pierce	NASA LaRC	HALOE airmass trajectory and photochemical modeling
R. Salawitch	NASA JPL	Photochemical steady state modeling
S. Solomon	NOAA AL	Interpretation of observations using a 2-D model
S. Strahan	NASA GSFC	Flight planning and constituent modeling using the GEOS-1 data assimilation system
A. Tuck	NOAA AL	SAGE II and HALOE data analysis and modeling

Table 5. (continued)

PI	Institution	Project Description
D. Waugh	Monash	CRC-SHM meteorological support and chemical modeling
S. Wofsy	Harvard	Analysis of ozone changes using SAGE II data and trajectories


Earth Probe TOMS 1997
90
75
60
45
30
15
0
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Jan
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FAI
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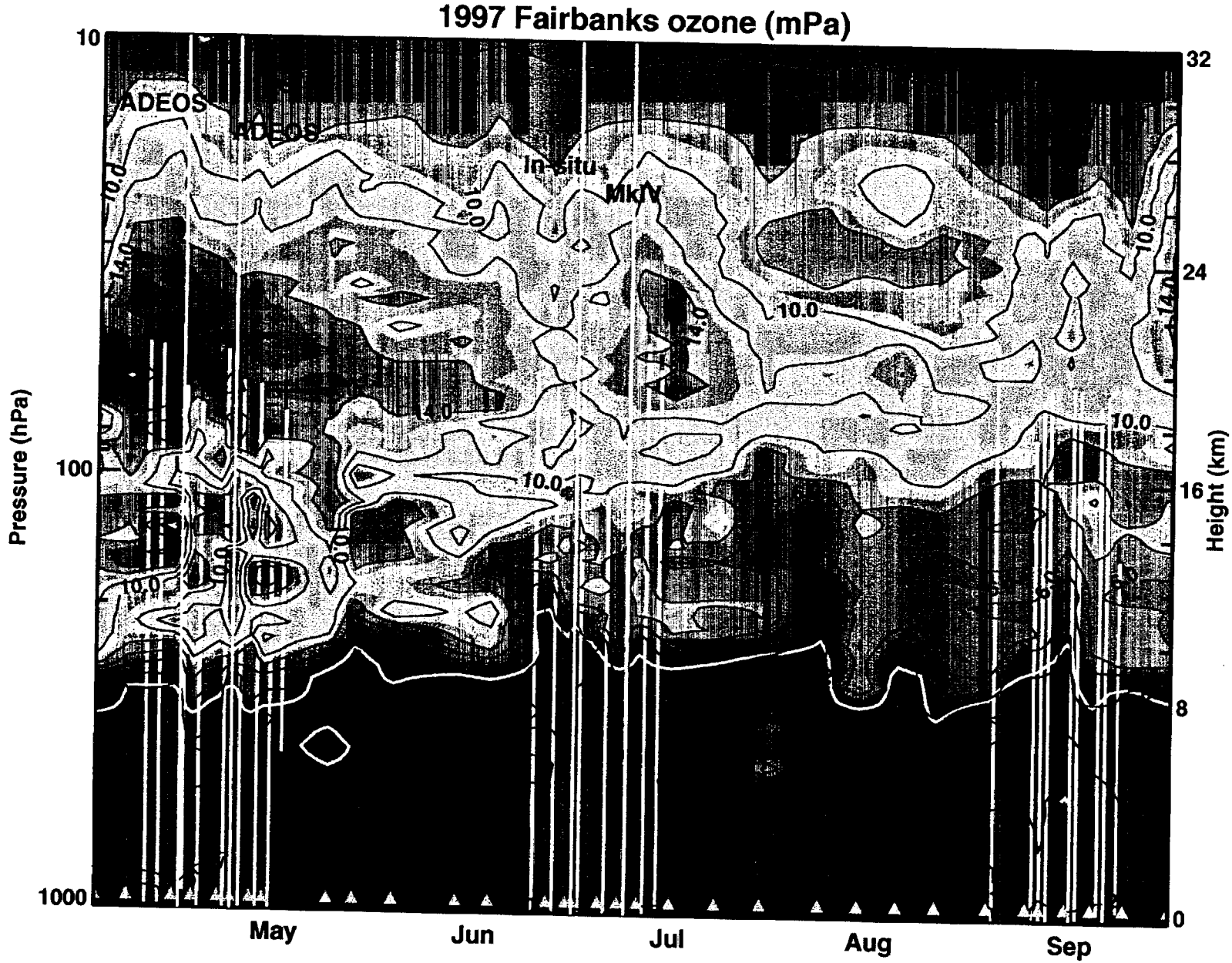
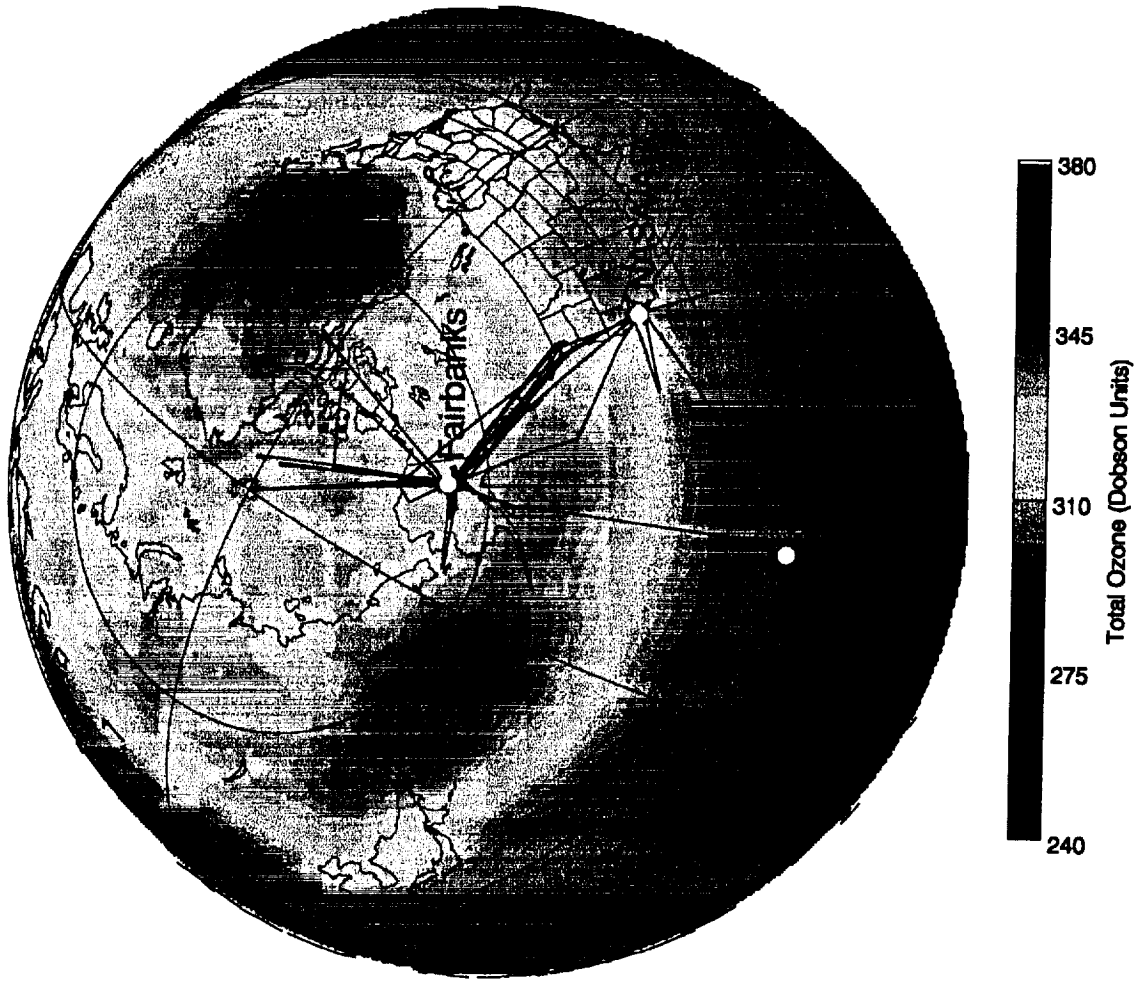
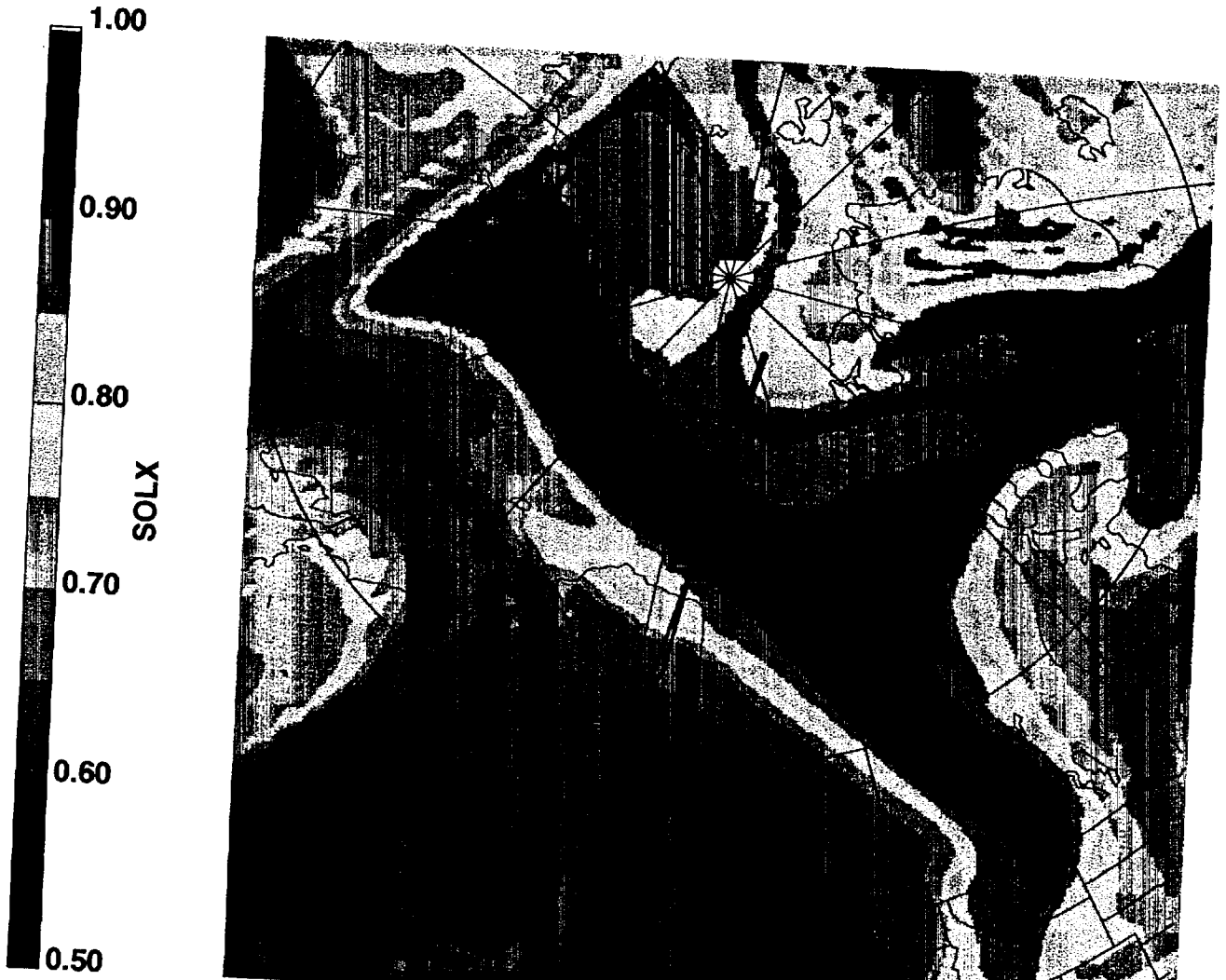
320
320
350
320
350
320
200
Dobson Units
425


1997 Fairbanks ozone (mPa)
ADEOS
ADEOS
In-situ
MkIV
10.0
14.0
10
100
1000
Pressure (hPa)
32
24
16
8
0
Height (km)
May
Jun
Jul
Aug
Sep

2


Fairbanks
380
345
310
275
240
Total Ozone (Dobson Units)


1.00
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SOLX
0.70
0.60
0.50